Low-Cost Hydrogen Distributed Production Systems
2006 DOE Hydrogen Program Review

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PD1

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HGM-2000

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Overview

Timeline

- Start: January 1, 2005
- Finish: January 31, 2008*
- ~30% complete

Budget

- Total project funding through Q1 2006
  - DOE: $850K
  - Contractor: $667.9K
- Funding received in FY05: $650K
- Funding for FY06: $200K

Barriers

- **Fuel Processor Capital Costs.**
- **Fuel Processor Manufacturing**
- **Operation and Maintenance (O&M).**
- **Feedstock Issues.**
- **Control and Safety**

Partners

- **Süd-Chemie, Inc.**
- **Naval Research Laboratory**

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*Given reduced funding to date, estimated completion date has slipped to at least September 30, 2008

Objectives

Execute on the following specific goals as part of the overall plan to overcome the barriers identified by the USDOE and to meet the USDOE technical targets in terms of cost and energy efficiency

- Design, build and test a 565 kg/day hydrogen plant for 99.999% pure hydrogen to meet DOE hydrogen $3/kg cost target for SMR and PSA
- Develop a catalyst suite based on our current technology suitable for use with fuel grade ethanol to facilitate renewable hydrogen production

Annual objectives

2005

- Achieve at least 3 kW increased heat recovery from the reformate in the HGM-2000 reformer
- Complete the design of features needed to boost the HGM-2000 capacity to at least 141 kg/day of CGA IB grade hydrogen in an HGM-2000 (30% increase)
- Demonstrate improved reforming and water gas shift catalysts for at least 2,500 hours of field testing in a full-scale HGM-2000
- Demonstrate improved PSA adsorbent technology to yield a 10% increase in hydrogen recovery.

2006

- Build & test HGM-2000 with 30% increased capacity
- Complete detailed design of HGM-10,000
- Demonstrate less than $350,000 BOM for HGM-10,000
- Operate pilot reactor on ethanol for >1,000 hours

Plan and approach for HGM-10,000

Technology	Original plan	Current plan	Ramifications
Reformer	design optimized reformer with new/different tube sizes, lengths, etc. and test in house.	Maximize parts commonality with HGM2000 machine to reduce short-term risk and cost	May require a 2nd, iterated design to optimize manufactured cost
PSA	Use DFMA techniques to optimize PSA dimensions. Build and test new, optimized PSA.	Employ multiple, duplicate PSA's based on proven, standardized parts	May require a 2nd, iterated design to optimize manufactured cost
Ancillaries	Build dedicated, in-house test plant to trial new ancillary concepts	Most concepts have been integrated incrementally into production machines, and are being tested in the field.	Higher risk/cost for H2Gen but faster schedule completion on curtailed budget.
Catalysts	Develop new catalyst sizes and compositions optimized for the geometry of the HGM10000	Focus on improving existing catalyst platform to maximize durability and minimize cost	overall reactor price/performance may suffer somewhat, resulting in a need for further development

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Performance achieved to date

2005 goal	Proxy figure	2005 goal	achievement to date	DOE targets	
				2005	2010
Achieve at least 3 kW increased heat recovery from the reformate in the HGM-2000 reformer	LHV fuel efficiency (w/ electricity)		68%	69%	70%
	LHV fuel efficiency		72%	N/A	N/A
Complete the design of features needed to boost the HGM-2000 capacity to at least 141 kg/day of CGA IB grade hydrogen in an HGM-2000 (30% increase)	ratio of output flowrates	130%	121%	N/A	N/A
Demonstrate improved reforming and water gas shift catalysts for at least 2,500 hours of field testing in a full-scale HGM-2000	runtime	2500	>2500	N/A	N/A
Demonstrate improved PSA adsorbent technology to yield a 10% increase in hydrogen recovery.	ratio CO adsorption breakthrough test time	110%	111.7%	N/A	N/A

- Eliminated need for PSA vacuum assist, saving capital cost, electrical consumption and O&M expense while increasing safety
- Successfully-demonstrated parallel-module PSA algorithm needed for HGM-10000
- Demonstrated low-electrical consumption, 60 psig natural gas feed machine

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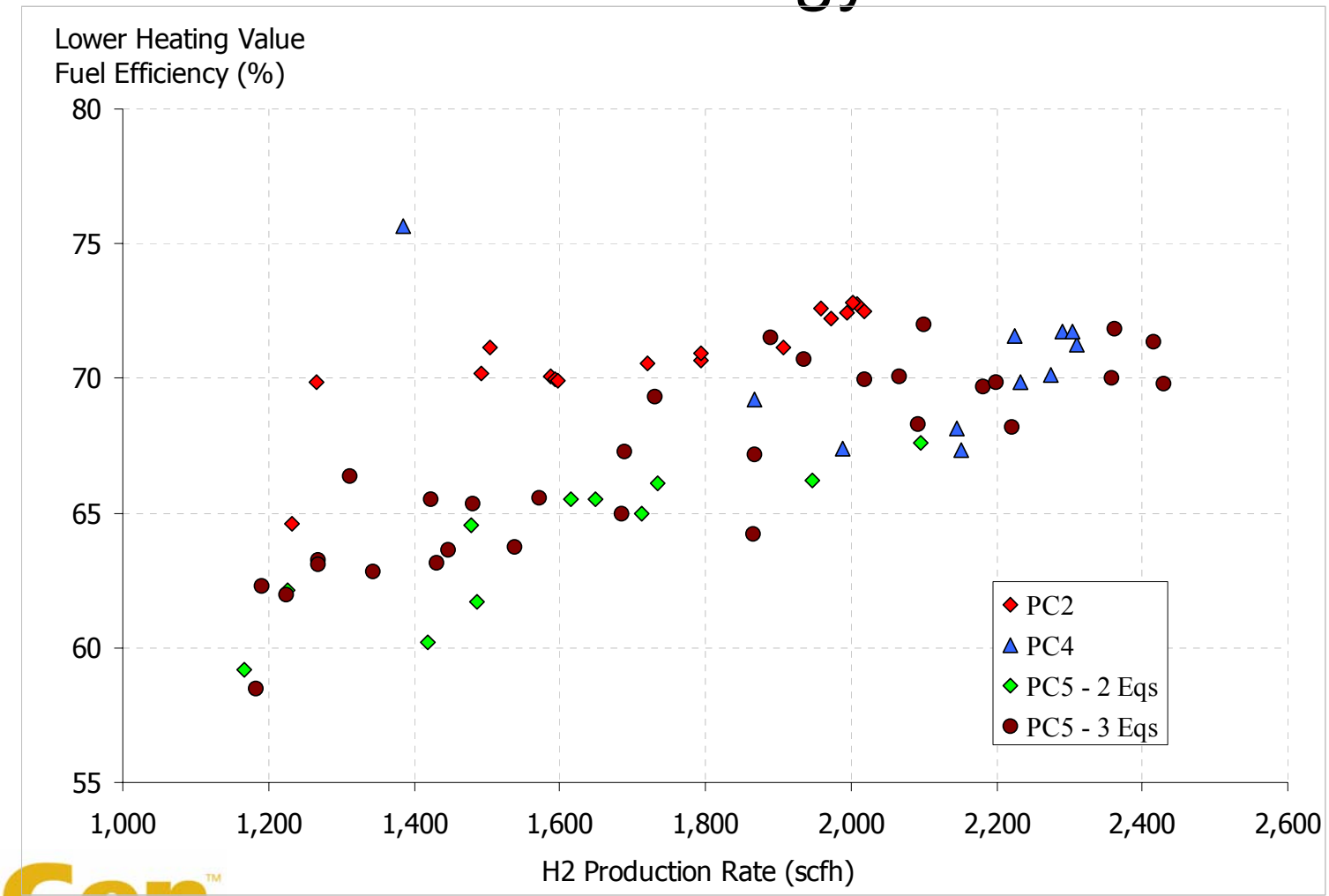
LHV Fuel Efficiency vs. Production Rate for HGM machines containing program technology



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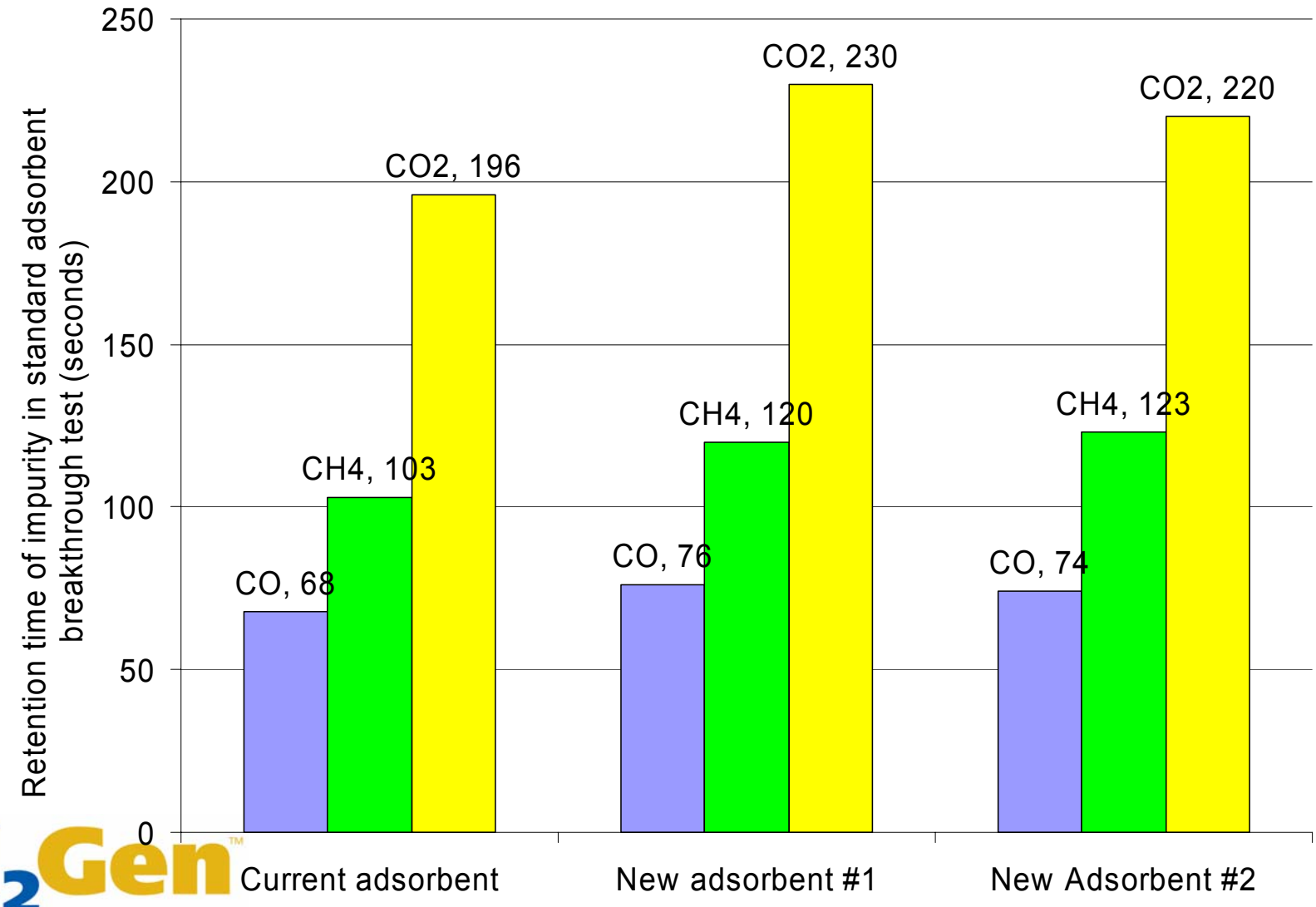
Different adsorbents have been identified which are 10% to 15% better than our current standard



HGM-10,000 new approach

- Limited funds require a new approach to HGM-10,000
- Pursuing maximum parts commonality to HGM-2000 to conserve funds
- Forces some “sub-optimal” design choices, but accelerates schedule
- Searching for development sites to defray costs for building first generation HGM-10,000
- A second, iterated design may be needed to reach the optimum economics (less parts commonality to HGM-2000, perhaps?)

Process differences for HGM-10,000

- Low pressure drop burner
- Low flue gas pressure drop “dual bundle” reformer, as per USDOE proposal – initial design complete
- Dual parallel PSA modules – like Japanese-market HGM2000 – optimization underway
- 300 psig operating pressure
- Air preheater to boost thermal efficiency a further 10% by further heat recovery from reformate

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H2 Cost Projections vs. DOE Goals

	HGM-2000	HGM-10,000	HGM-26,450
Capacity (kg/day)	113	567	1,500
Final Price FOB Alexandria	**$ 173,312**	**$ 472,732**	**$ 960,234**
Total Installed HGM Costs	**$ 225,812**	**$ 573,754**	**$ 1,111,069**
Hydrogen Costs ($/kg)			
Capital Recovery	1.71	0.78	0.57
O&M	0.47	0.23	0.15
Taxes & Ins	0.03	0.02	0.01
NG fuel	0.78	0.78	0.78
HGM Electricity	0.12	0.12	0.12
H2 Production Cost	3.12	1.92	1.62
Estimated Compression & Storage Costs ($/kg)			
Capital Recovery	2.06	1.01	0.743
O&M	0.144	0.071	0.052
Compression Electricity	0.11	0.11	0.11
Total Compression & Storage cost	2.31	1.19	0.90
Total Compressed H2 Cost ($/kg)	**5.42**	**3.10**	**2.52**
Total Compressed H2 Cost ($/gge)*	**2.29**	**1.31**	**1.06**

*On a range-equivalent basis with 2.4X better fuel Natural Gas = $4.5/MBTU; Electricity =5 cents/kWh

H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'HGM$';Q73 - 5 / 4 / 2006

Assumptions: H2A compression, storage & dispensing $$;

500 unit production;

70% capacity factor;

10% real, after-tax ROI (22.7% annual capital recovery factor)

DOE "All-in" H2 Cost Targets:

2005: $3/kg

2010: $2.50/kg

2015: $2/kg

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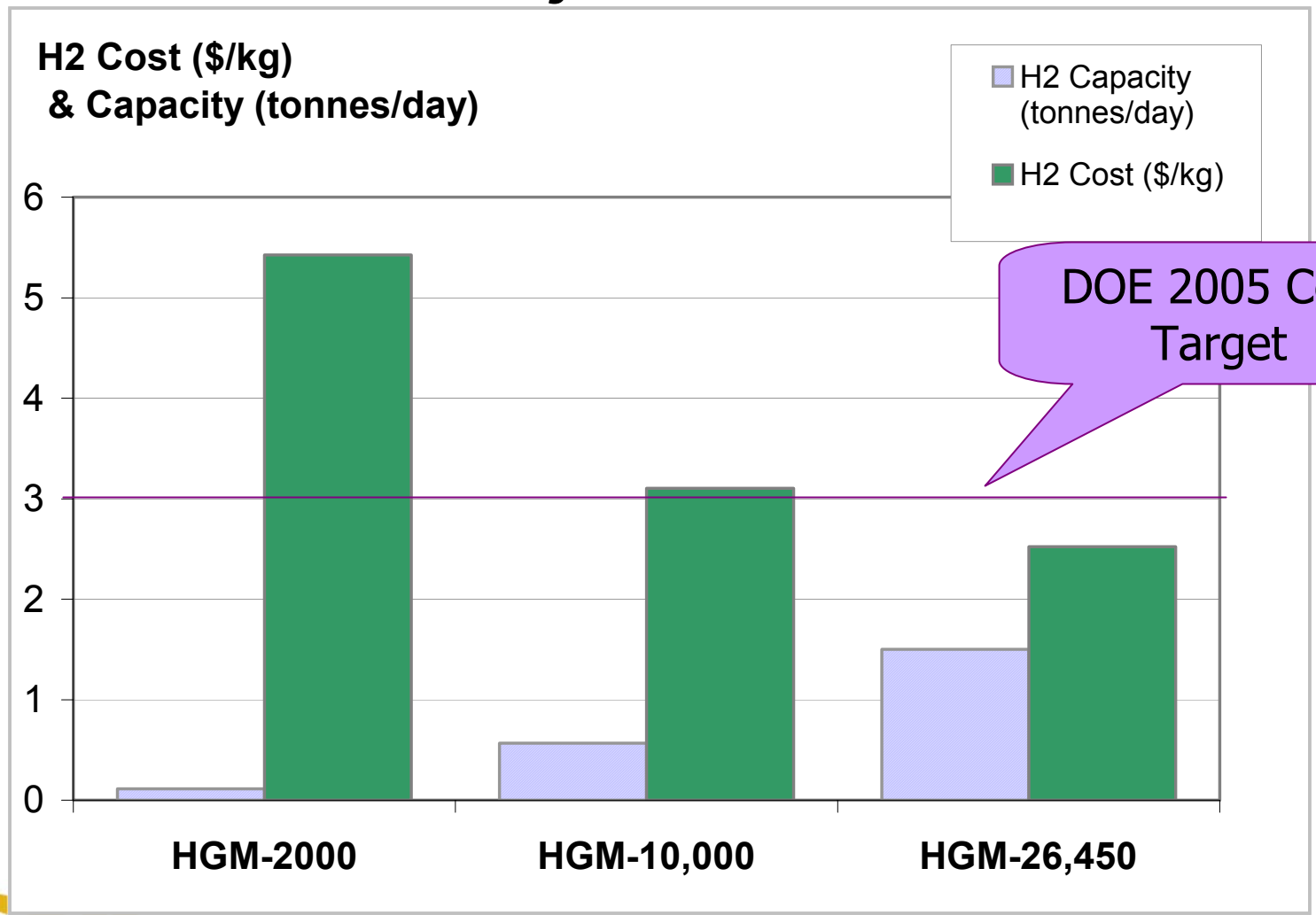
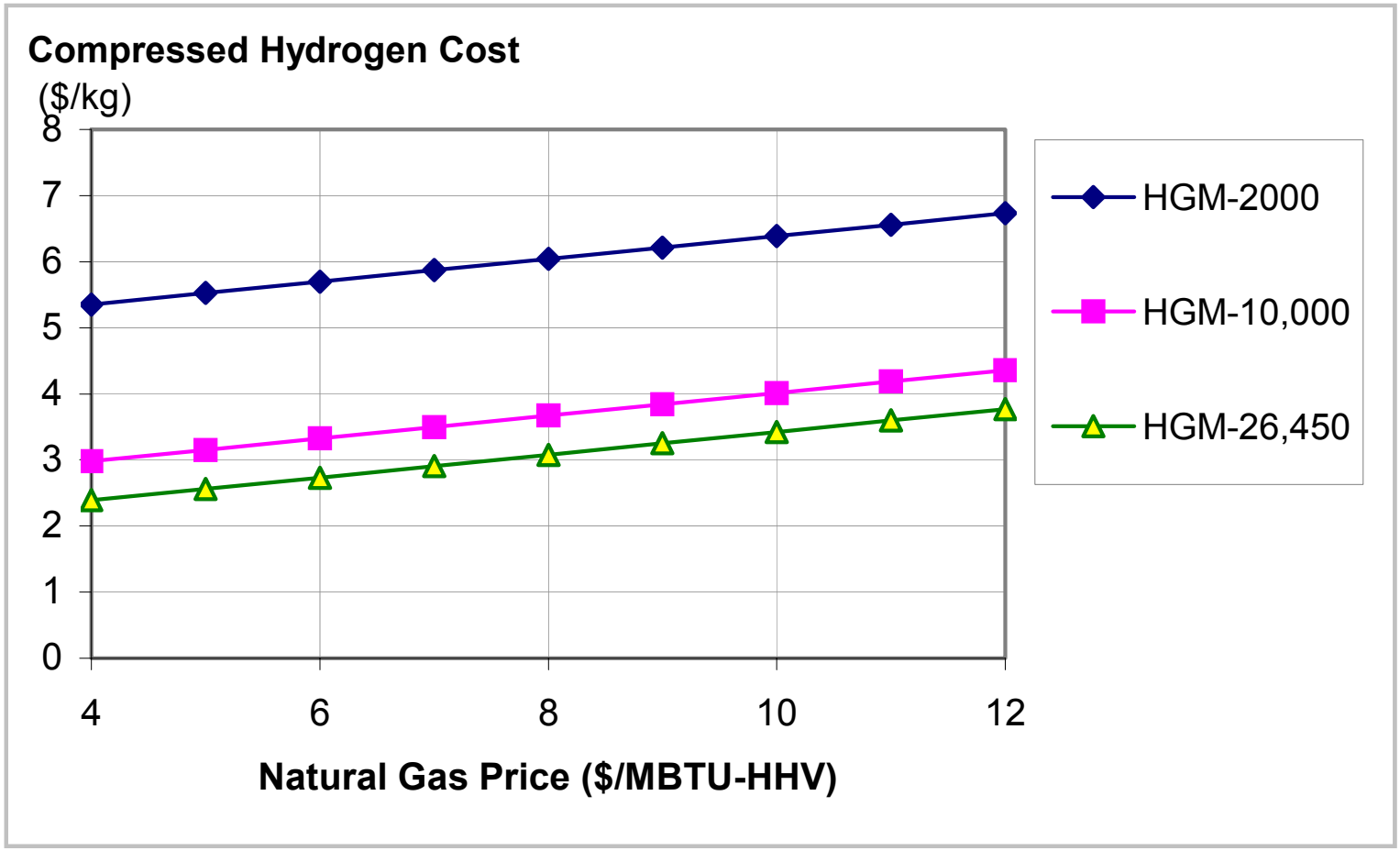
Compressed Hydrogen Cost Projections



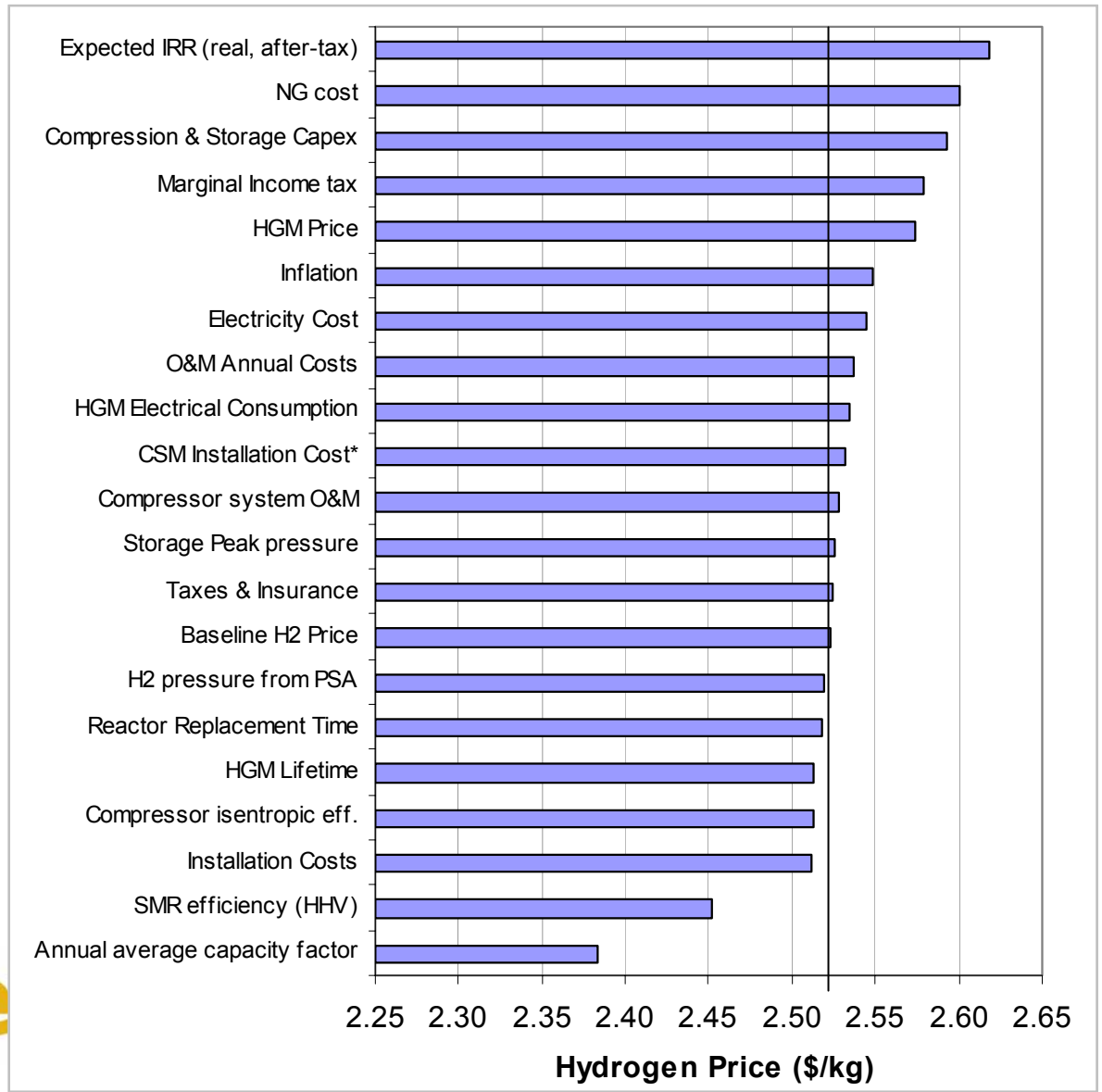
Natural Gas = $4.5/MBTU; Electricity =5 cents/kWh

H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'HGM$';Y87 - 1 / 12 / 2006

Natural Gas Price Impact on H2 Cost



H2 Price Sensitivity to 10% changes



Detailed Future Plans

- Extensive simulation in lieu of expensive system-level testing
- Full-scale bench testing of critical subsystems:
  - Burner and combustion ductwork
  - Steam generator
  - Condensor
  - Air preheater
- Final packaging to follow successful bench tests
- Full-scale apparatus to be completed on funds-available basis
- Ethanol pilot testing will begin in 2006

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Summary

- Despite curtailed funding, 2005 goals were largely achieved
- The project plan has been streamlined to maximize progress and minimize risk; this may require a 2nd iteration for the HGM10000 to optimize cost effectiveness
- Despite the changes, we believe that the HGM10000 deliverable should still demonstrate progress towards the USDOE goals

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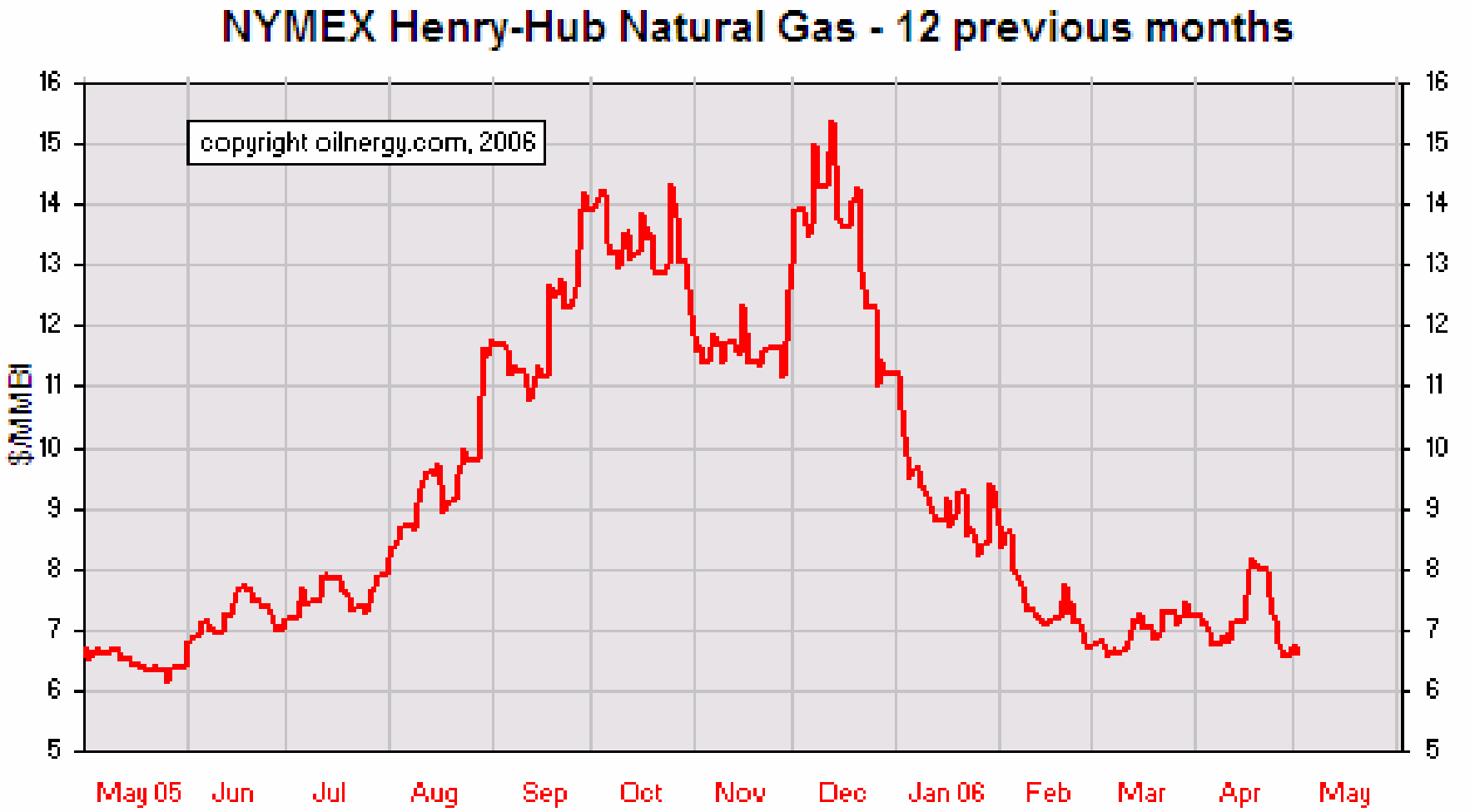
Back-up Slides

Critical Assumptions and Issues

- Natural gas prices will remain at or near projected values
- New burner performance will meet manufacturer's specifications
- Aromatic hydrocarbons and/or higher alcohols in ethanol can be steam reformed
- Shield-tube concept will perform as projected


NYMEX Henry-Hub Natural Gas - 12 previous months
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$/MMBtu
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Reconciliation of Original Bid Hydrogen Capital Cost Numbers

	HGM-2000 (Existing Platform)	HGM-10,000 (Built under DOE project)	HGM-26,450 (1,500 kg/day DOE baseline)
Original DOE Goal: $0.27/kg*	$91,000	$467,000	$1,209,000
H2Gen Goal: $0.21/kg*	$71,300	$355,000	$940,000

*Based on 11% annual capital recovery factor and 90% annual capacity factor and 500 unit/year production level

(22.7%/11% x 90%/70% = 2.65X increase)